Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 57/1/57/2 (1989)

Artikel: Durability of masonry strengthening by injection techniques

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DOI: https://doi.org/10.5169/seals-44296

Durability of Masonry Strengthening by Injection Techniques

Durabilité de maçonneries consolidées par des injections

Dauerhaftigkeit von durch Injektionen versteiftem Mauerwerk

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SUMMARY

Brick-masonry prisms, built with different types of mortar, were subjected to compression tests up to failure. The cracked prisms were injected with epoxy resin or cement-polymer grout according to a widely used repair technique. The mechanical improvement from the cracked situation, the penetration and diffusion of grout and the durability with respect to salt crystallization and thermal cycles was examined by means of destructive and non-destructive tests.

RÉSUMÉ

Des prismes de maçonnerie composés de briques liés avec différents mortiers ont été soumis à des essais de compression jusqu'à la ruine. Les prismes fissurés ont été injectés avec des résines époxydes ou des coulis de ciment modifiés avec des polymères. L'amélioration mécanique obtenue après l'injection, la pénétration et la diffusion du coulis ainsi que la durabilité à la cristallisation des sels et aux cycles thermiques ont été vérifiés par des essais destructifs, et non destructifs.

ZUSAMMENFASSUNG

Prismen von einem Ziegelmauerwerk, das mit verschiedenen Mörtelarten aufgebaut worden war, wurden den Druckprüfungen bis zum Bruch unterzogen. Die beschädigten Prismen wurden entsprechend einer sehr verbreiteten Reparaturtechnik entweder mit Epoxy-Harz oder mit Polymer-Zement eingespritzt. Zerstörende und zerstörungsfreie Versuche wurden angewandt, um die Verbesserung der mechanischen Eigenschaften, die Durchdringung und Ausbreitung der injizierten Stoffe und den Wiederstand gegen Salzkristallbildung zu untersuchen und zu bestimmen.

1. INTRODUCTION

Grouting by injection of resins and cement-polymer grouts is a strengthening and repair technique widely used for masonry in Italy and in most European countries.
A systematic experimental approach is needed to study the effectiveness of grouting for what concerns: the improvement of masonry strength, the degree of penetration and diffusion of the injected material and the durability of repairs to external agents such as temperature variation, frost-defrost action, etc. Furthermore a study of the interface between the grout and the existing materials is necessary in order to detect their bond strength.
Brick-masonry prisms were built with different types of mortar; some of them were submitted to a salt crystallization procedure set up by the authors which lead their external surfaces to decay. The strength and deformability of the prisms were evaluated by compression tests; care was taken in order to avoid a total destruction of the specimens.The damaged prisms were successively strengthened by injection of epoxy resin or cement-polymer grout and subjected again to the compression test.
Some of the repaired prisms were instead submitted to the crystallization test in order to detect the durability of grouting when masonries are exposed to aggressive environments. The influence of temperature variation on the mechanical characteristics (compressive strength, deformability, bond-strength) of small specimens repaired by epoxy resin and subjected to thermal cycles was also measured.
When dealing with in service masonry structures, a way to detect the actual conditions of the materials and to evaluate the efficacy of the injection technique could be drilling of cores and inner inspection. However this checking is of destructive nature with significant sampling difficulties. Ultrasonic pulse transmission tests were used as a mean to check penetration and diffusion of grout and measure the degree of strengthening in masonries repaired by injection. The aim was to verify the effectiveness of this non destructive technique. The results obtained were controlled by cutting some prisms into slices and by verifying the quantity and position of voids after injection.

2. EXPERIMENTAL AND GROUTING PROCEDURE

Twenty five prisms (25x52x60 cm) were prepared with one type of solid brick and three types of mortar: pozzolana-lime (M1), cement-lime (M2) and high strength cement modified with acrylic resins (M3). Detailed information on the mortar composition and on brick properties are given in [1]. Some of the prisms were then subjected to a crystallization test in order to simulate the masonry decay due to external aggressive environments [2]. The deteriorated prisms made with mortar M1, M2, M3 were respectively named MU1Ti, MU2Ti, MU3Ti where i = 1, ..., n1 (n2, n3), represents the number of the prism. The reinig undamaged prisms were named MU1i, MU2i, MU3i (where i = 1, ..., n1 (n2, n3)).
All the prisms were subjected to compression tests. The tests were performed using an MTS hydraulic servocontrolled machine at a constant rate of displacements of 0,00095 m/s. The testing recommendations [3] were adopted. The prisms which had not reached a total collapse were then repaired by injection, some with an epoxy resin, some with a grout composed of cement and a 10% of the same epoxy resin. The resin was a two component one, mixed before injection. Its pot life is 60 to 40 min, the setting time 6 to 4h between 15 and 22°C, the compressive strength 110 MPa, the tensile strength 70 MPa and the elastic modulus 3,000 MPa.The injections were carried out after the external surfaces of the cracked prisms were impermeabilized with a thick epoxy paint. Detailes of the operation are described in [4]. After injection and appropriate curing, the prisms were again subjected to the compression tests above mentioned.

Three prisms repaired with epoxy resin were cut into slices, in order to check the degree of diffusion and penetration of the resin.
Three prisms injected with epoxy resin were subjected to the crystallization test described in [5] in order to study the behaviour of the repaired masonry to aggressive environment. At every cycle the specimens, after a 4h immersion in a saturated solution of Na_2SO_4, were exposed for 7 days at 20°C and 50% R.H.

Small stack-bond prisms repaired with epoxy resin were subjected to thermal cycles in order to detect the effect of the temperature variation on the strength and deformability of masonry injected with polymeric materials (8h at 60°C and 70% R.H., 16h at 20°C and 50% R.H. or 16h at -15°C and 8h at 20°C and 50% R.H.); a detailed description of the test and results is given in [5].
During every phase of the experimental work (before the compression test, after the compression test, after injection and finally after testing again the prisms up to collapse) some of the prisms were controlled by ultrasonic pulse transmission tests. Two 90 kHz-wave transducers were used and the pulse transmission data (velocity and waveform) were monitored along horizontal path both in longitudinal and transverse directions. More detailed information are found in [1].

3. RESULTS AND DISCUSSION

The results of the different experimental procedures adopted to detect the effectiveness and durability of repair by injection technique are reported in the following.

3.1 Mechanical tests

Detailed de scription of the compression tests carried on MU1i, MU2i, MU3i and MU1Ti, MU2Ti, MU3Ti prisms are reported in [1], [5] where tables and figures are used also to show the correlation of the compressive strength of injected prisms, to the quantity of injected resin or cement-polymer grout and to the number of injections. Apparently no correlation exists between the compressive strength and the injection pressure, which for some prisms reached 0.55 MPa, but which is recommended to be taken as low as possible (in some recommendations no more than 0.05 MPa).
In fig. 1 an example is given of the most representative stress-strain curves of prisms after injection with epoxy resin together with their original curves. The following comments can be made:
- The strength $\bar{\sigma}_r$ (corresponding to the maximum load carrying capacity) of the injected prisms is always higher than the value σ^* at which the previous compression test was stopped (Fig.1).
- The strength $\bar{\sigma}_r$ of the injected prisms reaches an average of 85% of the strength σ_r originally attained by prisms.
- The stress-strain curves of the injected prisms tend to remain similar to those of the prisms under the first compression test (Fig.1). In other words the injections of epoxy resin apparently do not give a totally new situation in terms of deformability; in fact the influence of the mortar used for the masonry is definitely prevailing even after injection. Nevertheless a tendency to an increasing in brittleness is detected.

The same experimental investigation was carried on four prisms injected with cement-polymer grout. At presently only some comments on the first risults can be made:

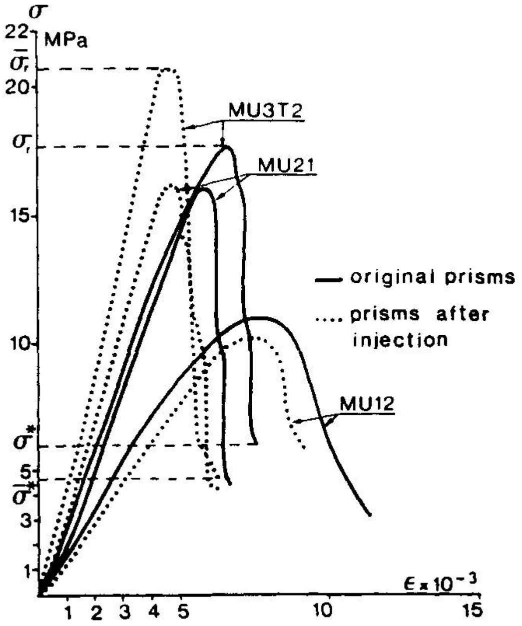

Fig. 1 Stress-strain curves for prisms injected with resin

- The strength $\bar{\sigma}_r$ of the injected prisms is still higher than the value σ^* at which the previous compression test was stopped, but it does not attain more than the 40% of the value σ_r originally reached by the prisms.

- The slope of the σ - ε curves of the injected prisms tends to be lower than the one given during the first compres- test. Nevertheless after the value $\bar{\sigma}_r$ is reached a tendency is shown to a reduc- in brittleness, if comparison is made to the original situation.

3.2 Ultrasonic pulse transmission tests

Based on all ultrasonic velocity measures obtained on the prisms at the several phases considered (undamaged, damaged, injected, collapsed), a rough guide for the evaluation of the masonry condition can be stated, slightly different from that one proposed by other authors [6]:

- velocities of less than 1400 m/s indicate highly cracked masonry with very poor mechanical properties (less than 3,5 MPa compressive strength);
- velocities between 1400 and 2400 m/s indicate a lower quantity of cracks and an appreciable compressive strength (between 3,5 and 10,5 MPa);
- velocities over 2400 m/s indicate masonry in a good normal condition.

The average values measured at the various phases of the experimental work are reported in Fig.2 for all the masonry prisms: the positive grouting effects are clearly visible, particularly for the prisms injected with epoxy resin. The high value of velocity measured on MUjTi prisms is due to their content in sodium sulphate. Moreover a relationship, even if quite rough, has been noticed between

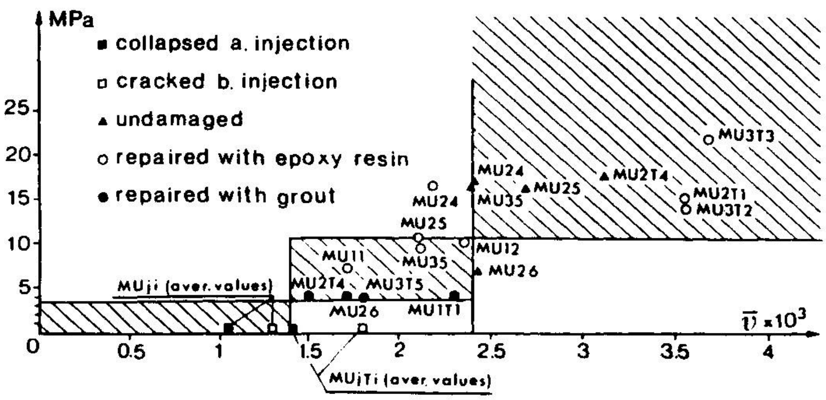

Fig. 2 Rough guide for quality masonry

velocities and strength. The ratio between the masonry strengths in the undamaged condition and after injection (0.85 and 0.40 respectively for epoxy resin and resin modified mortar grouting) was found similar to the ratio between the relative average velocities. If confirmed by further experimental data, the pulse velocities could then be considered as reliable to define the global changement of the material characteristics after repair by injection. Finally, taking into account also the waveforms of the ultrasonic pulses and comparing their amplitudes and frequencies in the different phases considered, more detailed local information on the grouting penetration and diffusion have been obtained. In fact in some cases locally increased velocities did not correspond, in the waveform, to increased values of amplitude and to a general increase in the signal components with higher frequency. Thanks to inner observation (see Sec. 3.3) this situation could easily be connected with the presence of cracks and voids that the injected material has only partially filled.

3.3 Penetration and diffusion of the grout

In order to control the information given by the sonic tests and to know the local state of penetration and diffusion of the injected grouts, the three prisms, one for every type of mortar, cut into slices were carefully investigated. A map of the crack distribution was drawn; in several cases an high percentage of voids was detected.
The inspection of the cut surfaces and of the failure mode of the prisms shows that he external crack distribution does very seldom correspond to the internal one so that external cracks do not connected with internal.
Two different situations were observed:

a) Injection of epoxy resin:
   the resin filled better wide open cracks (5 ÷ 7 mm) than narrow cracks (0.2 ÷ 2.5 mm) and cracks in mortar joints. In several cases the resin was absorbed by the brick (5 to 6 mm of impregnation) while the cracks remained empty (Fig.3). This impregnation, beside changing the colour of the injected brick (Fig.4), decreases the brick porosity and increases its mechanical strength.

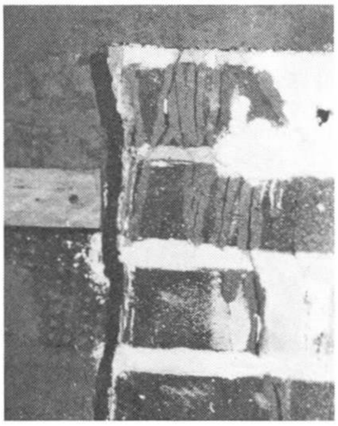

Fig. 3 Penetration of salts inside cracks and voids

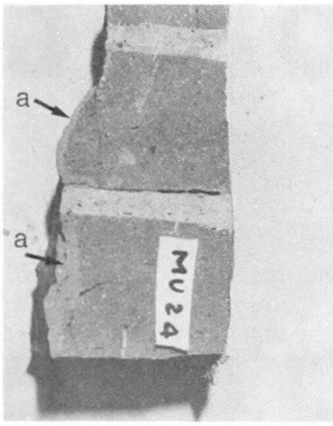

Fig. 4 Fracture along the boundary of the impregnated zone (a)

b) Injection of cement-polymer grout:
   the grout had better filled the cracks than the resin, but shrinkage phenomena took place in various cases and also the formation of bubbles was observed when air was trapped inside cracks [5].

3.4 Durability tests

Three prisms, one for each type of mortar (M1, M2, M3), where subjected to the described crystallization test for 16 cycles.
The sodium sulphate was transferred and deposited by capillary rise inside voids and unfilled cracks and, sometime, caused a propagation of cracks. Injections cannot prevent the penetration and diffusion of salt solution inside the masonry if they do not fill all voids (Fig.3).

Small specimens (3 or 4 brick stack-bond prisms) repaired with epoxy resin were subjected to thermal cycles. The mechanical tests carried on the prisms after 63 cycles allowed to state that temperature variations influence the behaviour of masonries repaired with resin: freeze tends to increase the material stiffness and the brittleness; while thaw, decreases its stiffness and strength [5].

CONCLUSIONS

Up to now, some conclusions can be drawn concerning particularly the repairs made with epoxy resin (which on the other hand are not so frequently used in practical cases without a filler).
An improvement of the mechanical strength of cracked masonry is the consequence of the injection of resin. Resin does not influence the stiffness of the masonry apart from a tendency to a more evident brittleness in the case when the brittle behaviour is typical of the original masonry.
Uniform penetration and diffusion or resin into cracks and voids is seldom realized if external cracks do not connect with internal ones. Water and salts can easly penetrate into small unfilled cracks and deteriorate the material.
Temperature variations can influence the behaviour of the repaired masonry and produce internal states of stresses caused by the variation of properties of the resin thermal cycles.
Based on the results obtained in this experimental work the technique of the ultrasonic pulse velocities measurements can be a practical tool in the assessment of the masonry conditions and a reliable way in the evaluation of the grouting efficiency. The waveform analysis of the ultrasonic pulse can give useful information on the grout penetration and diffusion into the masonry, as increased velocity alone can not assure a complete filling of voids and cracks. However a large presence of such discontinuities generally represents an obstacle in the interpretation of ultrasonic measurements.
The next step of the research, which is partly supported by a EEC Stimula Research Contract, will be to study the behaviour of prisms injected with other types of epoxy resin, the variation of bond strength when the technique is applied in the presence of moisture inside masonry and to continue the research on the effectiveness of cement-polymer grouts.

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